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GPS MULTIPATH ERRORS IN THE PRECISION LANDING ENVIRONMENT

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SUMMARY

Aircraft guidance and positioning during the final approach and landing phases of flight requires a high degree of accuracy. The Global Positioning System operating in differential mode (DGPS) is being considered for this application. Prior to implementation, all sources of error must be considered. Multipath has been shown to be the dominant source of error for DGPS. Theoretical studies have verified the severity of multipath within the final approach and landing regions. This paper presents a study of GPS multipath errors during these critical phases of flight. A discussion of GPS multipath error characteristics will be presented along with actual multipath data. The data was collected using P-code and C/A-code receiver architectures. Data was collected onboard a dual-engine fixed-wing research aircraft. Aircraft dynamics are considered in the data analysis.

INTRODUCTION

GPS soon will have the capability to provide position information to users anywhere in the world nearly 24-hours per day. For applications requiring precise positioning (better than one meter), a stand alone installation is not sufficient to provide adequate positioning accuracy. However, differential GPS (DGPS) can provide users with sub-meter level accuracies. Aircraft guidance and positioning in the final approach and landing phases of flight is a prime example of an application for DGPS.

At Ohio University's Avionics Engineering Center, the use of DGPS for aircraft guidance and positioning during final approach and landing is being investigated. GPS by itself has many sources of error including Selective Availability (SA), ionospheric delay, tropospheric delay, receiver hardware errors, receiver noise and multipath. DGPS eliminates those errors which are common to both receivers. The single largest source of error that remains is the error due to multipath (ref. 1). If DGPS is to be used for final approach and landing, the effects that multipath has on the GPS range measurements must be characterized and controlled to meet the required error budgets. This paper will present a discussion of multipath characteristics and multipath errors observed during the final approach and landing phases of flight. Aircraft dynamics are considered in the data analysis.

BACKGROUND

The accuracy of GPS positioning depends on the accuracy of the pseudorange measurements. There are many error sources which cause erroneous range measurements. The major error sources are as follows:

- signal delay due to propagation through the troposphere
- signal delay due to propagation through the ionosphere
- error due to satellite clock offset and orbit uncertainty
- Selective Availability (SA)
- receiver inter-channel biases
- receiver measurement errors
- dynamics
- thermal noise
- specular multipath
- diffuse multipath

Although differential carrier phase measurement accuracies are typically better than two centimeters, the code phase measurements are still required for ambiguity resolution. Therefore, this paper focuses on the code phase measurement error. The signal at the receiver is a combination of different types of signals: direct and non-direct. The direct signal is the signal received that travels the geometric distance from the satellite to the receiver. The non-direct or multipath signal is a signal that has been reflected or diffracted off an object and arrives at the receiver after the direct signal. In most cases the multipath signal is weaker than the direct signal. When the direct and the multipath signals combine, the result is a signal with the same frequency but having a relative phase difference with respect to the original direct signal. This phase error effects both the code measurement and the carrier phase measurement.

DGPS eliminates the errors in the measurements that are common to both receivers. Multipath has a different effect on each receiver. This is because multipath depends on the GPS antenna environment. For a typical DGPS system, the receivers are not close enough to each other to possess the same multipath characteristics. Three categories of multipath for the final approach and landing environment are (ref. 2):

- Obstacle-based at the airborne receiver.
- Airframe-based at the airborne receiver.
- Obstacle-based at the ground reference station receiver.

The air and ground system obstacle-based multipath originates from the ground itself as well as from buildings or other structures on or near the ground. The airframe-based multipath radiates from the airplane's wings and fuselage.

DATA COLLECTION

GPS multipath data collection was performed in the vicinity of the Ohio University Airport (UNI) located near Albany, Ohio. The grounds surrounding UNI are relatively flat and free of clutter. There are two large fixed structures (hangars) that are capable of generating significant multipath. Overall, UNI can be considered a benign multipath environment with the leading contributor being the ground itself. The GPS antenna used during the data collection was a duel frequency microstrip antenna.

A 12-channel GPS receiver was used for the data collection. The receiver is capable of continuous tracking the C/A-code on the L1 carrier (1575.42 MHz) and the P-code on both the L1 and the L2 carrier (1227.6 MHz). The measurement data from the GPS receiver was collected and recorded in real time using a 386-based notebook computer.

Data was collected over a 70 minute time period. The flight path is shown in figure 1. The aircraft remained stationary on the taxiway for 15 minutes and then proceeded to the end of the runway for takeoff. The airborne portion of the flight was approximately 40 minutes. After takeoff, a 180-degree left turn was executed and the aircraft climbed to 4000 feet. Then the aircraft flew out 15 miles and executed another 180-degree left turn. Completing the race track maneuver, the DC-3 flew over the runway at 600 feet. The aircraft then executed a 180-degree left turn while climbing to 1500 feet and then traveled 6 miles at level flight. At that time a tear drop maneuver was performed. After the tear drop maneuver, a 90-degree left turn was completed that aligned the aircraft for the final approach into UNI. After landing the airplane taxied and then remained stationary for another 15 minutes.

DATA PROCESSING TECHNIQUES

The combination of multipath, thermal noise, unknown bias and receiver error was extracted from the data using the standard code-minus-integrated Doppler technique (refs. 3 and 4). Equation (1) shows the result:

$$\begin{aligned} d_{code} - d_{phase} &= 2d_{iono} + d_{code-meas} \\ &- d_{phase-meas} + d_{code-noise} \\ &- d_{phase-noise} + d_{code-mp} \\ &- d_{phase-mp} - \Delta + d_{other} \end{aligned} \tag{1}$$

where:

d_{code}	is the code phase measurement
d_{phase}	is the carrier-phase (integrated doppler) measurement
$_{iono}$	is the signal delay due to propagation through the ionosphere

$d_{code\text{-}noise}$	is a combination of thermal noise and diffuse multipath on the pseudorange
$d_{phase\text{-}noise}$	is a combination of thermal noise and diffuse multipath on integrated carrier phase
$d_{code\text{-}meas}$, $d_{phase\text{-}meas}$	is receiver measurement noise for code and phase measurements
$d_{code\text{-}mp}$, $d_{phase\text{-}mp}$	is specular multipath on the code and phase
Δ	is an integer wavelength ambiguity
d_{other}	includes receiver measurement error and dynamics

For situations where the strength of the multipath is less than the direct signal, the carrier-phase multipath term will not exceed 4.8 centimeters (ref. 2). It has been shown that state-of-the-art receivers exhibit phase-noise values on the order of 0.1 millimeter (1-sigma) (ref. 5) allowing this term to be neglected as well. The receiver phase measurement error is also negligible (ref. 6). The carrier-phase multipath, the noise and the receiver phase measurement terms can all be dropped from equation (1) because the code-multipath error is usually on the order of meters and they are very small compared to that term. The integer ambiguity is a constant bias for the duration of the data collection, which is not of interest for this study. Equation (1) can be approximated by:

$$(d_{code} - d_{phase})' = 2d_{iono} + d_{code\text{-}meas} + d_{code\text{-}noise} + d_{code\text{-}mp} + d_{other} \tag{2}$$

The error due to the propagation delay through the ionosphere can be removed through the standard dual-frequency correction (refs. 2 and 7):

$$d_{iono_{f1}} = \left(\frac{f2^2}{f2^2 - f1^2}\right)\left(d_{code_{f1}} - d_{code_{f2}}\right) \tag{3}$$

Noise is reduced by averaging (filtering) the code measurements against the stable carrier measurements. This is done using a Hatch filter. The Hatch filter implementation for this application averaged over 100 seconds of data (ref. 8). After applying the ionospheric correction and the Hatch filter, we arrive at the following:

$$(d_{code} - d_{phase})'' = d_{code\text{-}meas} + d_{code\text{-}mp} + d_{other} \tag{4}$$

The next section presents the results of the data collection and data analysis.

DISCUSSION OF RESULTS

The results are presented in figures 2 through 10, and table 1. The code-minus-carrier for satellites 2, 6, 11, 15 and 19 are shown in figures 2 through 6 respectively. Figure 7 shows the elevation angles for the satellites during the flight test. As anticipated, the larger error levels are correlated to the lower elevation angles. Table 1 shows the root mean squared (rms) of the multipath error in meters for the C/A-code and the P-code for each satellite for four dynamic conditions: static, taxing at airport, airborne and the final approach. The last row in the table represents the average for all the satellites for both the C/A-code and the P-code for each phase of flight. The smallest average errors are encountered during the final approach phase of flight which had relatively low dynamics with respect to the other flight phases.

With respect to the in-flight data, preliminary analysis indicates that the dynamics seem to correlate with the excursions found in the code-minus-carrier traces. Figures 8 through 10 show the aircraft velocities for the data collection in the east, north and up directions. Clearly, the changes in velocity are correlated with some of the excursions in the multipath data, especially satellite 2. The excursions seen in the multipath plots could be a result of either the dynamics affecting the receiver tracking loops or the banking of the aircraft causing the antenna to be exposed to additional multipath from the wing or the ground. The errors are more predominant during low-altitude turns. This may lead one to conclude that the excursions are indeed a result of multipath. However, this cannot be certain, more study is required to determine the exact cause of the excursions. The data shown in figures 2 through 6 represent the data used for the ambiguity resolution. It is important to understand these deviations to achieve reliable in-flight ambiguity resolution.

CONCLUSIONS

From the data presented in this paper, we conclude that even in a benign environment, measurable multipath error exists. We also found that dynamics have a noticeable effect on multipath errors. Much work is needed in the area of multipath mitigation. Although the P-code represents a tremendous improvement over the standard C/A-code in multipath performance, total immunity has not been achieved. This must be done if DGPS is to be implemented for final approach and landing of aircraft.

ACKNOWLEDGEMENTS

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TABLE 1.- SUMMARY OF MULTIPATH ERRORS

	Static		Taxi		Flight		Final Approach	
	C/A rms (meters)	P rms (meters)	C/A rms (meters)	P rms (meters)	C/A rms (meters)	P rms (meters)	C/A rms (meters)	P rms (meters)
SV2	1.127	0.749	0.721	0.233	0.640	0.362	0.315	0.075
SV6	1.272	0.339	0.607	0.161	0.435	0.360	0.367	0.291
SV11	1.040	0.643	0.768	0.547	0.570	0.287	0.883	0.385
SV15	0.679	0.359	0.570	0.370	0.610	0.367	0.405	0.261
SV19	0.708	0.189	0.762	0.179	0.695	0.156	0.932	0.182
average	0.96	0.46	0.69	0.30	0.59	0.31	0.58	0.24

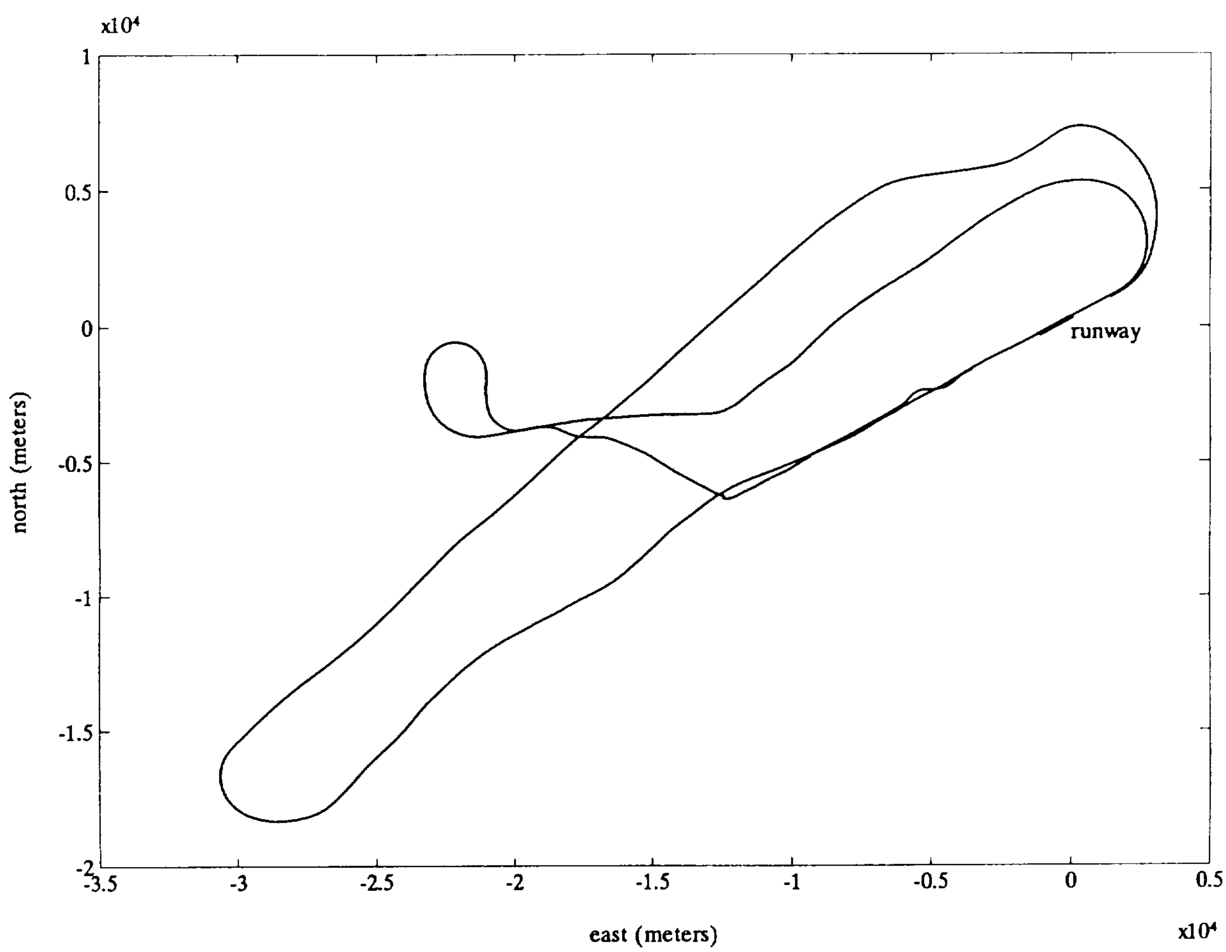

Figure 1. Aircraft flight path in East-North coordinates.

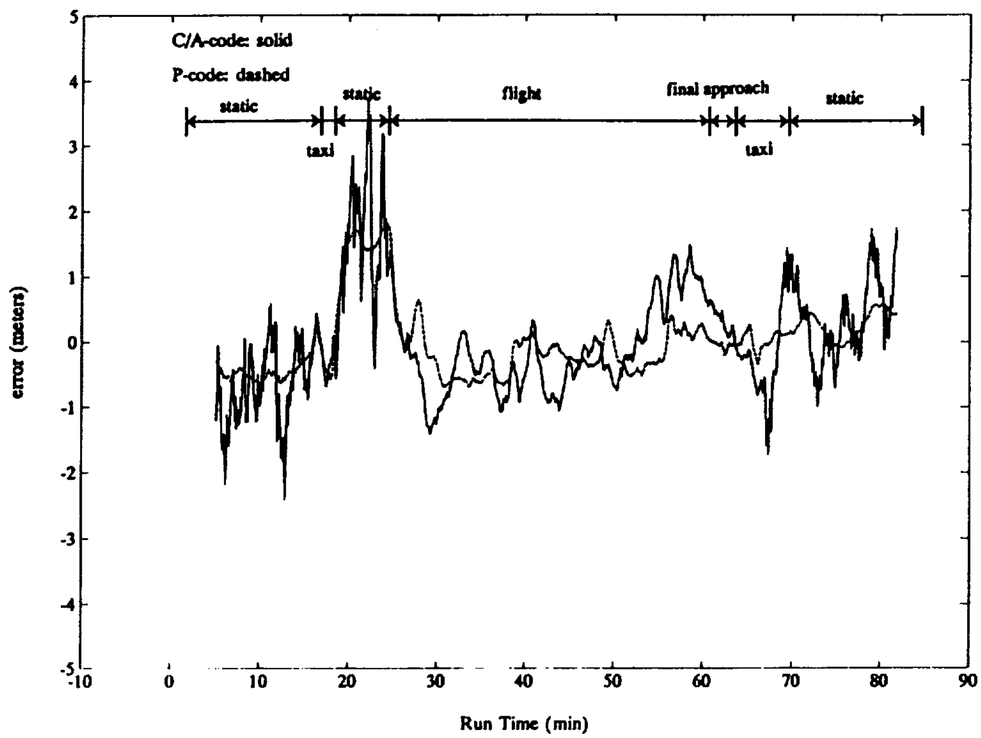

Figure 2. Satellite 2 multipath, thermal noise, unknown bias, and receiver error.

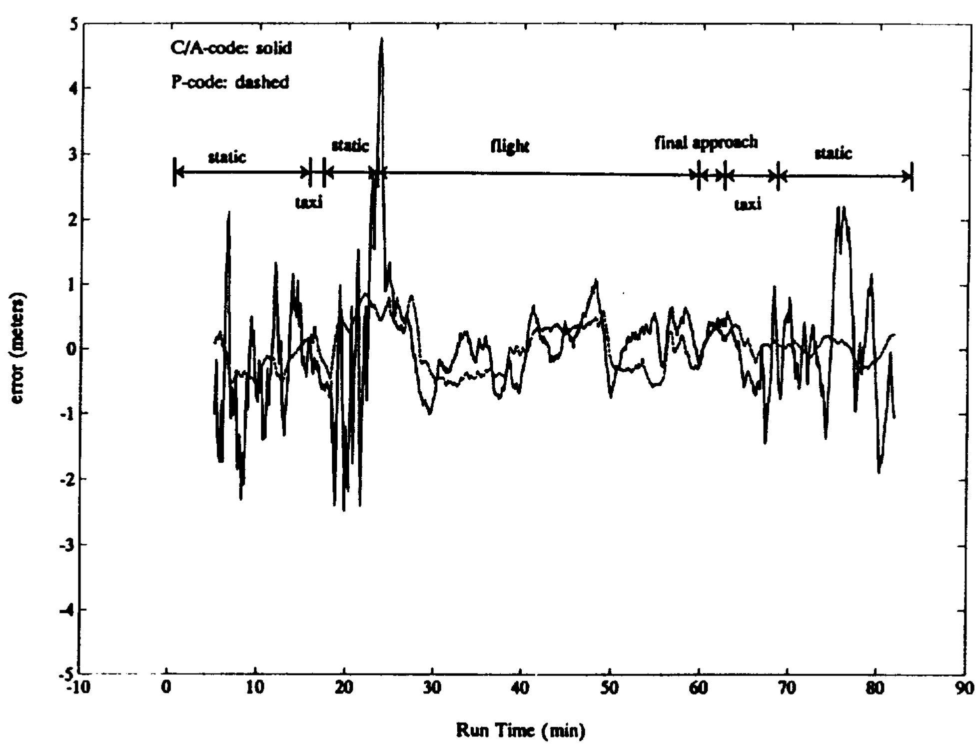

Figure 3. Satellite 6 multipath, thermal noise, unknown bias, and receiver error.

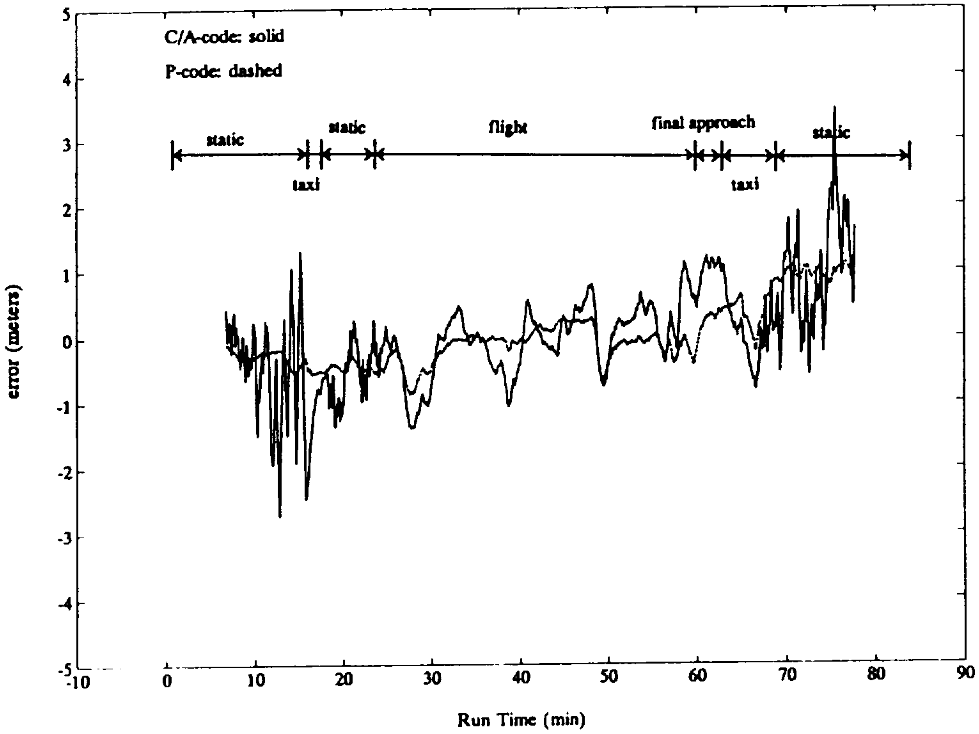

Figure 4. Satellite 11 multipath, thermal noise, unknown bias, and receiver error.

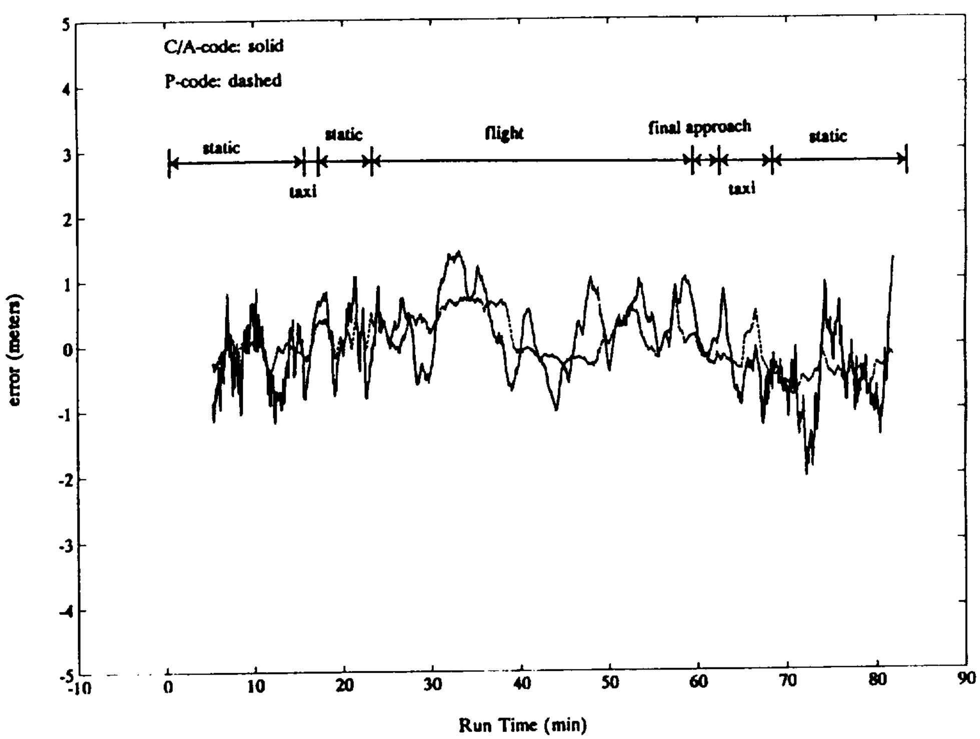

Figure 5. Satellite 15 multipath, thermal noise, unknown bias, and receiver error.

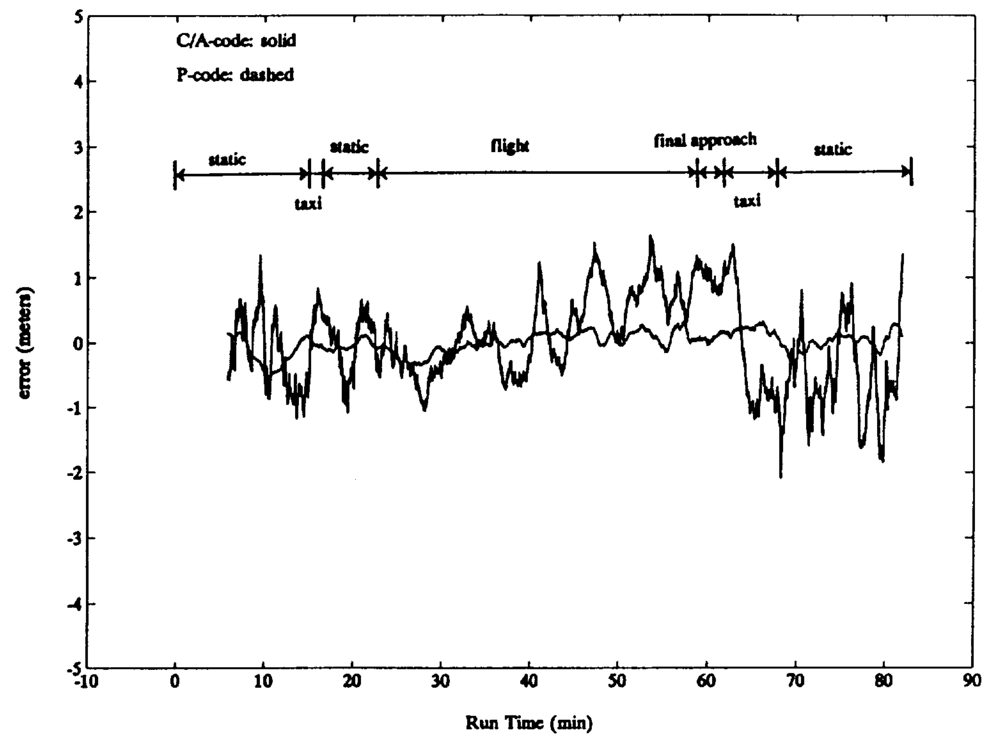

Figure 6. Satellite 19 multipath, thermal noise, unknown bias, and receiver error.

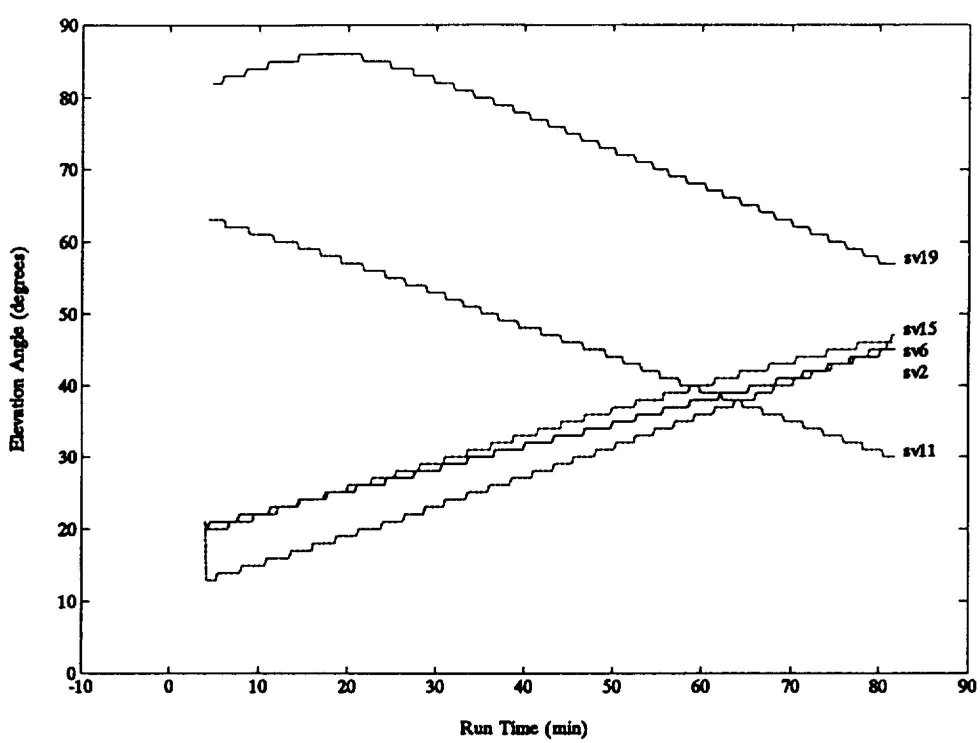

Figure 7. Satellite elevation angles as a function of time.

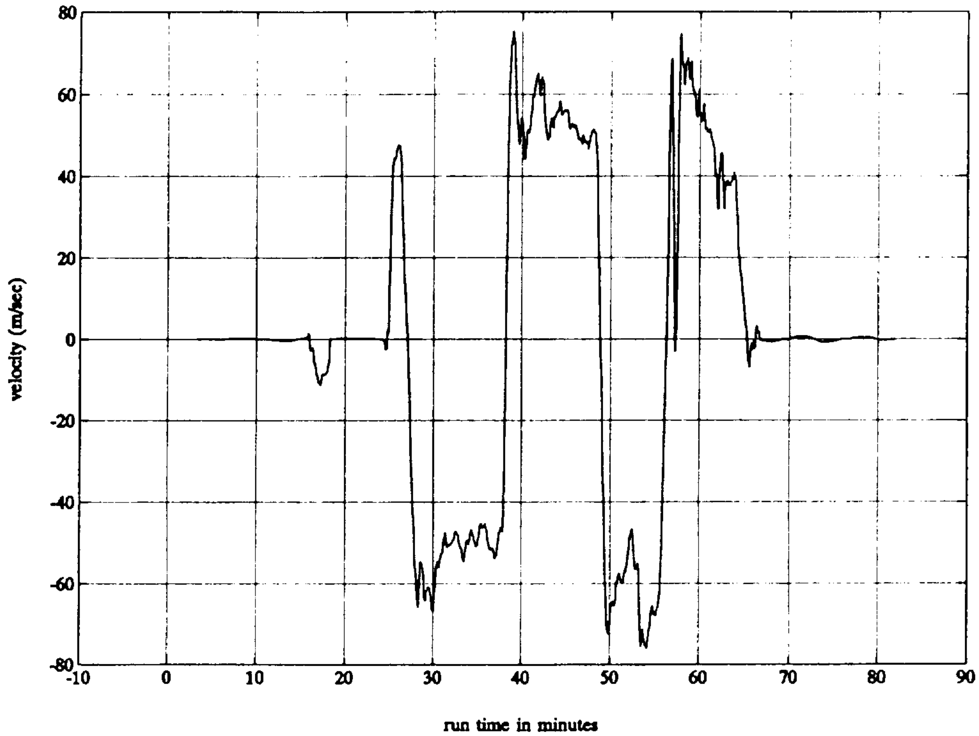

Figure 8. Aircraft velocity in the East direction as a function of time.

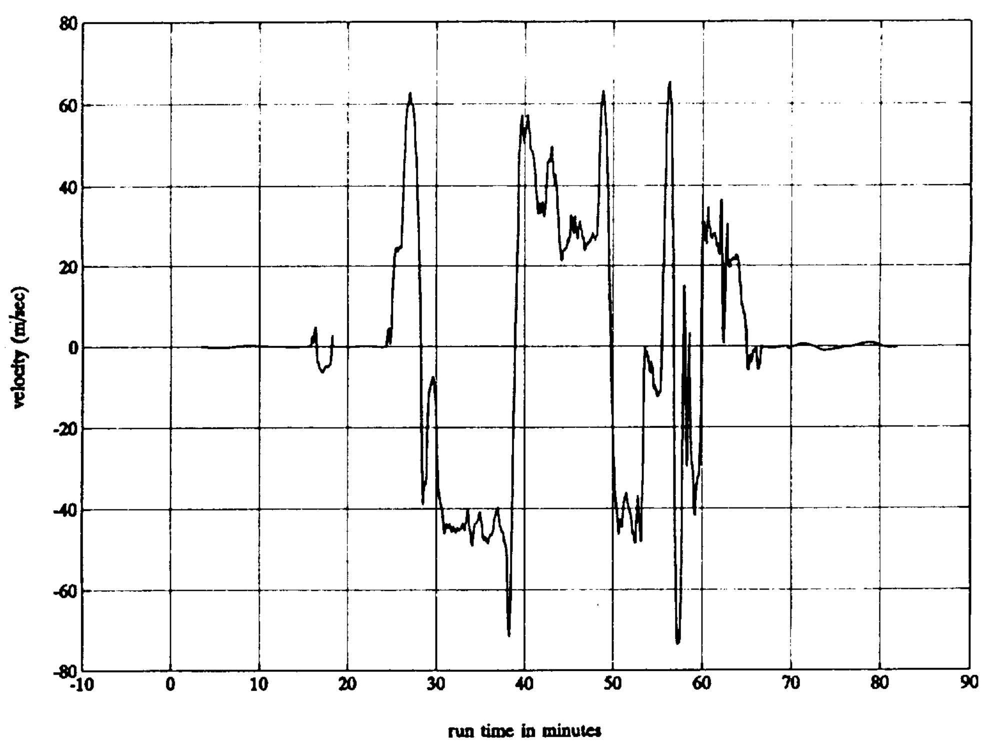

Figure 9. Aircraft velocity in the North direction as a function of time.

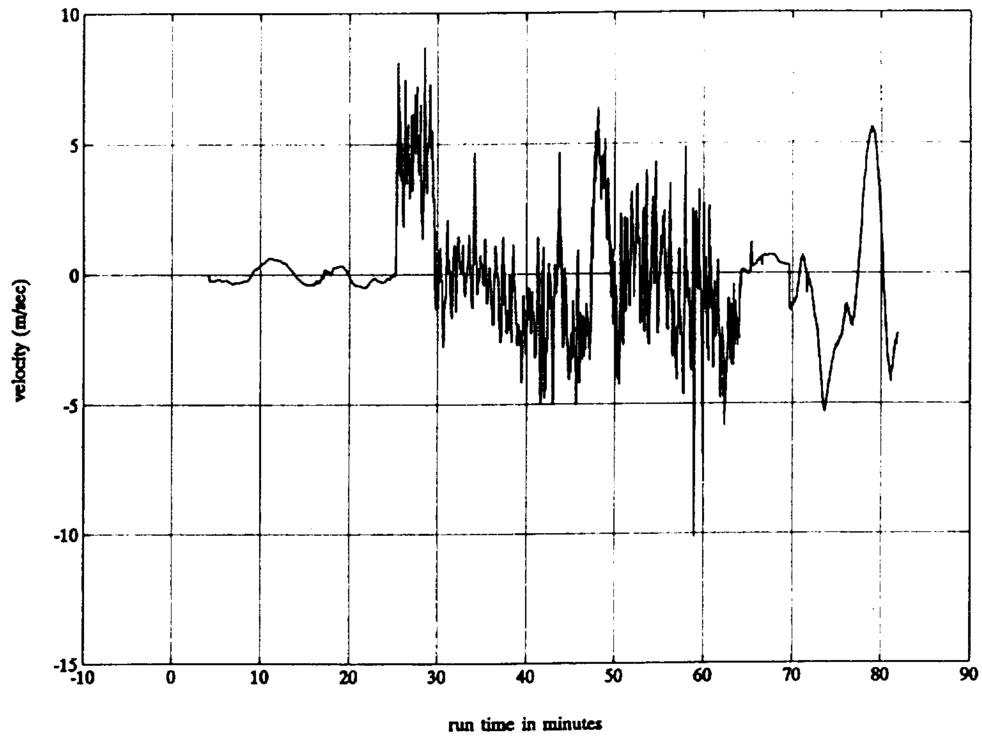

Figure 10. Aircraft velocity in the Vertical direction as a function of time.

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